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Jet Propulsion Laboratory
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Nearby **E**xo-Earth **A**strometric **T**elescope (NEAT)

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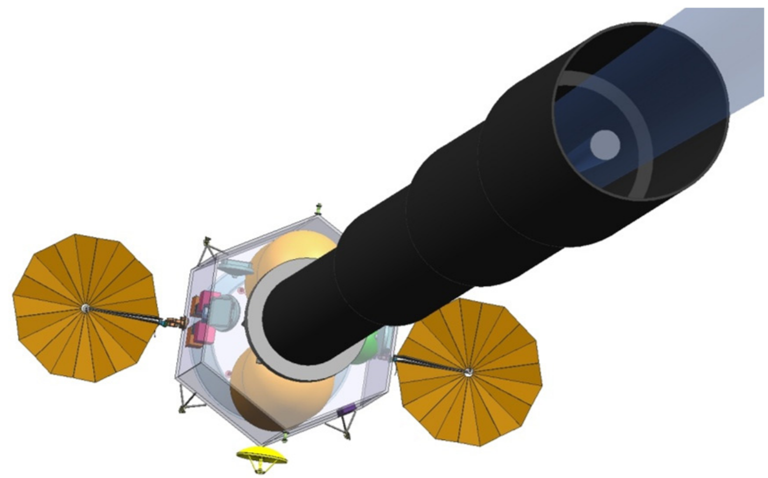
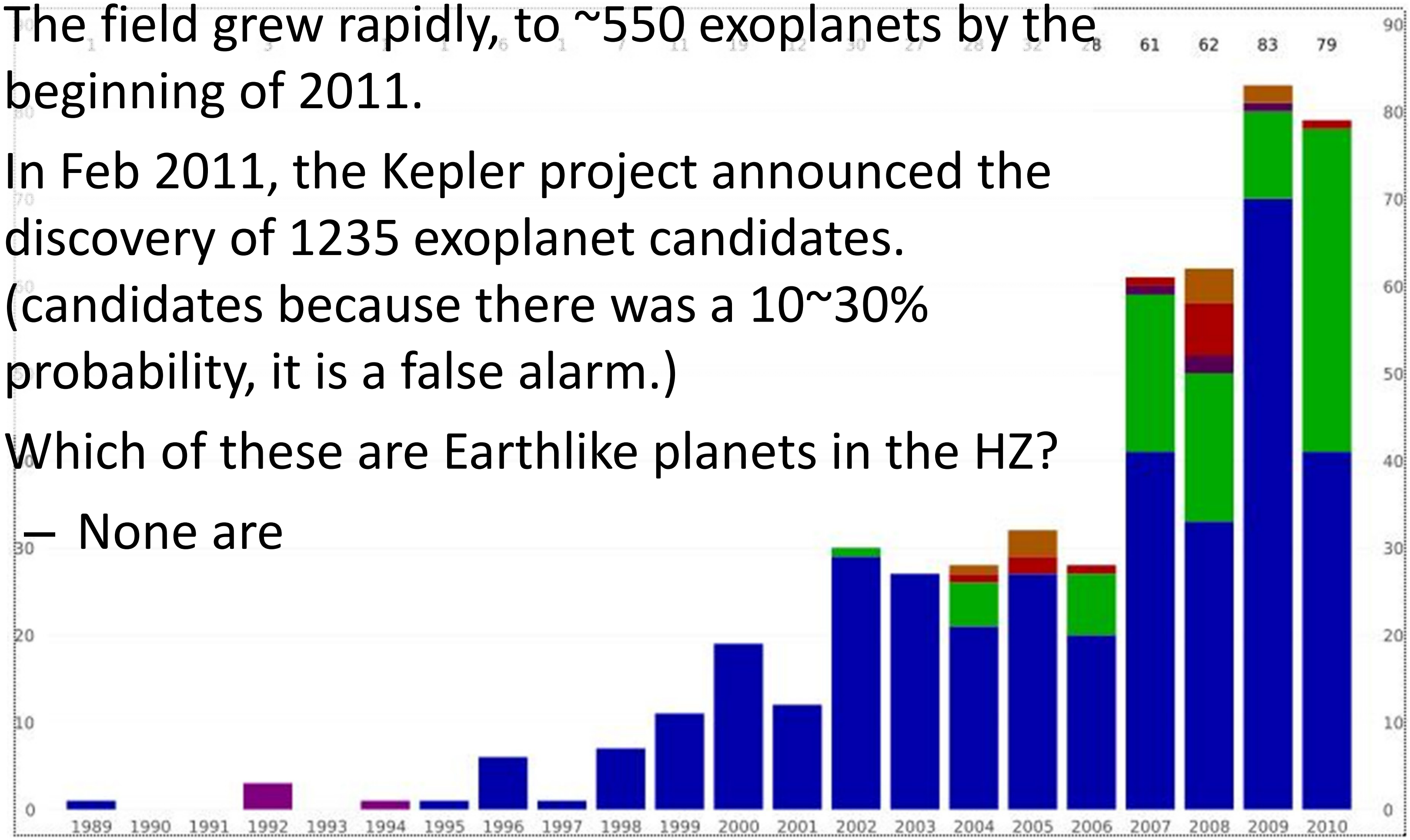
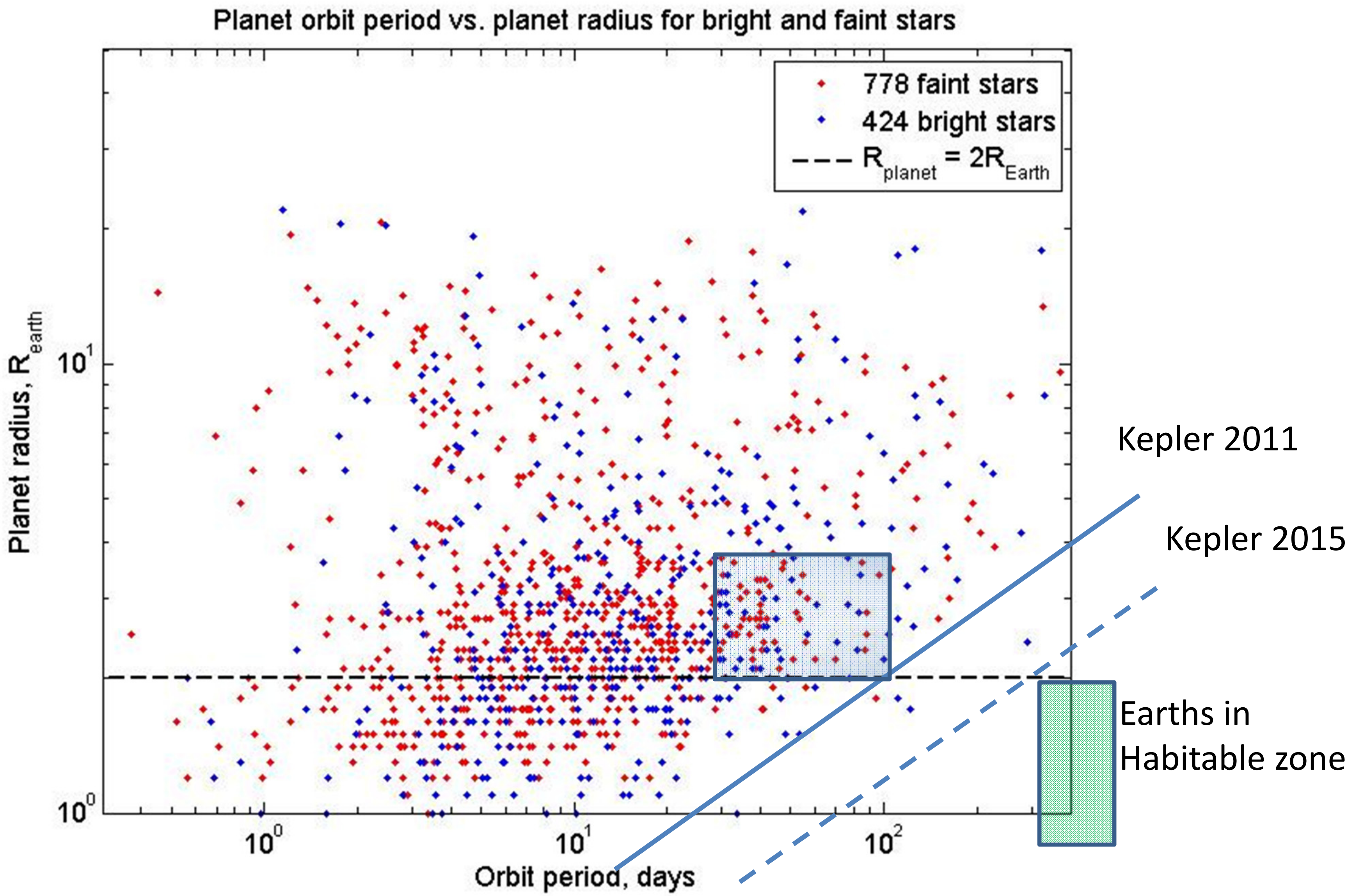


Exoplanets

- The first planet (around a star) outside of the solar system was discovered in 1995, 51 Peg, by Mayor and Queloz (Geneva).
- The field grew rapidly, to ~550 exoplanets by the beginning of 2011.
- In Feb 2011, the Kepler project announced the discovery of 1235 exoplanet candidates. (candidates because there was a 10~30% probability, it is a false alarm.)
- Which of these are Earthlike planets in the HZ?
  - None are



Kepler Exo-Planets



Catanzarite, J., Shao, M. , The Occurrence Rate of Earth Analog Planets Orbiting Sunlike Stars , to appear in ApJ (Aug 2011).

Major Technical Issues for uas Astrometry

- In astrometry with a telescope, what are the major obstacles, that led us to the SIM design?
  - **Photon noise**. The target stars are bright, photon limit is from the reference stars (SIM's 2 deg DIA)
  - **Beam walk** (optical errors). The stellar footprint on secondary, tertiary is different for different stars in the FOV. (more on this later)
  - **Focal plane** array **stability**. (Mosiac of ccd's) (1e-11)
  - **Intra-pixel QE variations/PSF**
    - Pixels are not uniformly spaced @ 1e-5 pixels
    - Pixel QE's are not uniform across 1 pixel to 1e-5
    - The Optical PSF changes by lambda/100 across the field.
    - Centroiding to a few*1e-3 pixels has been demonstrated.
  - **SIM related technology provides solutions to the last 2 problems**

Photon Noise

- Nominal 1m telescope 0.36 sqdeg fov
  - 0.71 uas in 1 hr (photon limit from ref stars)
  - SIM-Lite performance 1.0 uas 2axis, in 1 hr

	1m	1.4m
0.4 deg	0.94 uas	0.48
0.6 deg	0.71	0.36
0.8 deg	0.58	0.29 uas

R band 640nm 25% bw
Total QE 60% (ideal 85%)
Use photons from brightest 6 ref stars
ref stars (avg for sky from AQ4)

#ref stars	5	6	7	10	100
phot noise	0.73	0.71	0.69	0.65	0.52 uas
faintest	11	11	11	12	14 mag

CCD can run at 25C (but very slightly better at 0C)

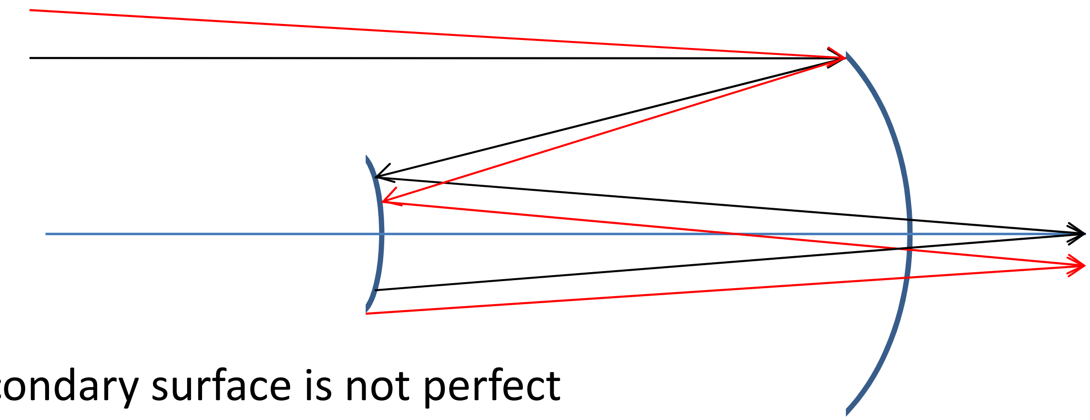
If target star < 8 mag, photon noise from target not important
Photon noise from laser metrology not important.
Lasers turned on ~3% of time, every ~ minute (depending on therm stab)

Photon Noise is Not an Issue
What's the Best Astrometry with a Telescope?

- Ground based astrometry is limited by atmospheric turbulence
- In Space, HST astrometry (with CCD camera) is perhaps the most accurate. ~100uas. (λ/D ~40mas, critically sampled, 1/200 pixel)
- With NEAT we hope to do 1uas (in 1 hr) with a 1m telescope.
  - 100X higher accuracy with ½ smaller telescope
  - Centroid to 1/50,000 pixel
- How is this possible? (this is the wrong question to ask) The right question is what are the systematic errors that prevent HST from doing 1uas astrometry.

Beam Walk Error in Normal Telescope

- 1 uas (across a 1m mirror) is 5 picometer/1m. 1/20 the diameter of an atom.



•If the secondary surface is not perfect
at the 5pm level there will be systematic biases > 1uas.
•Biases that are constant (for 5yrs) are OK. But 5pm stability is not
possible for any optic over 5 yrs.

Detailed simulation results of **Beam walk error** in a 3 mirror TMA telescope (O. Guyon) would be **0.5~1 milliarcsec** if the secondary and tertiary optics are polished to **1nm** accuracy. Beam walk errors are smaller for smaller angles ~10uas for 10 arcsec field.

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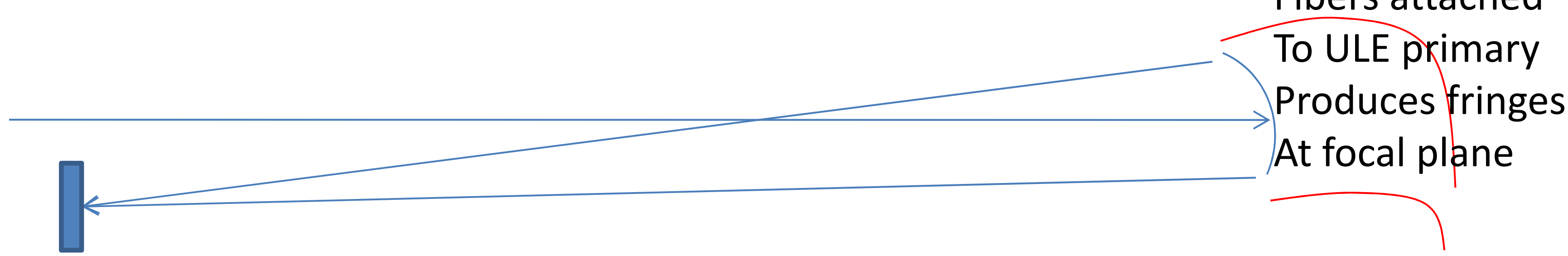
NEAT Telescope Concept



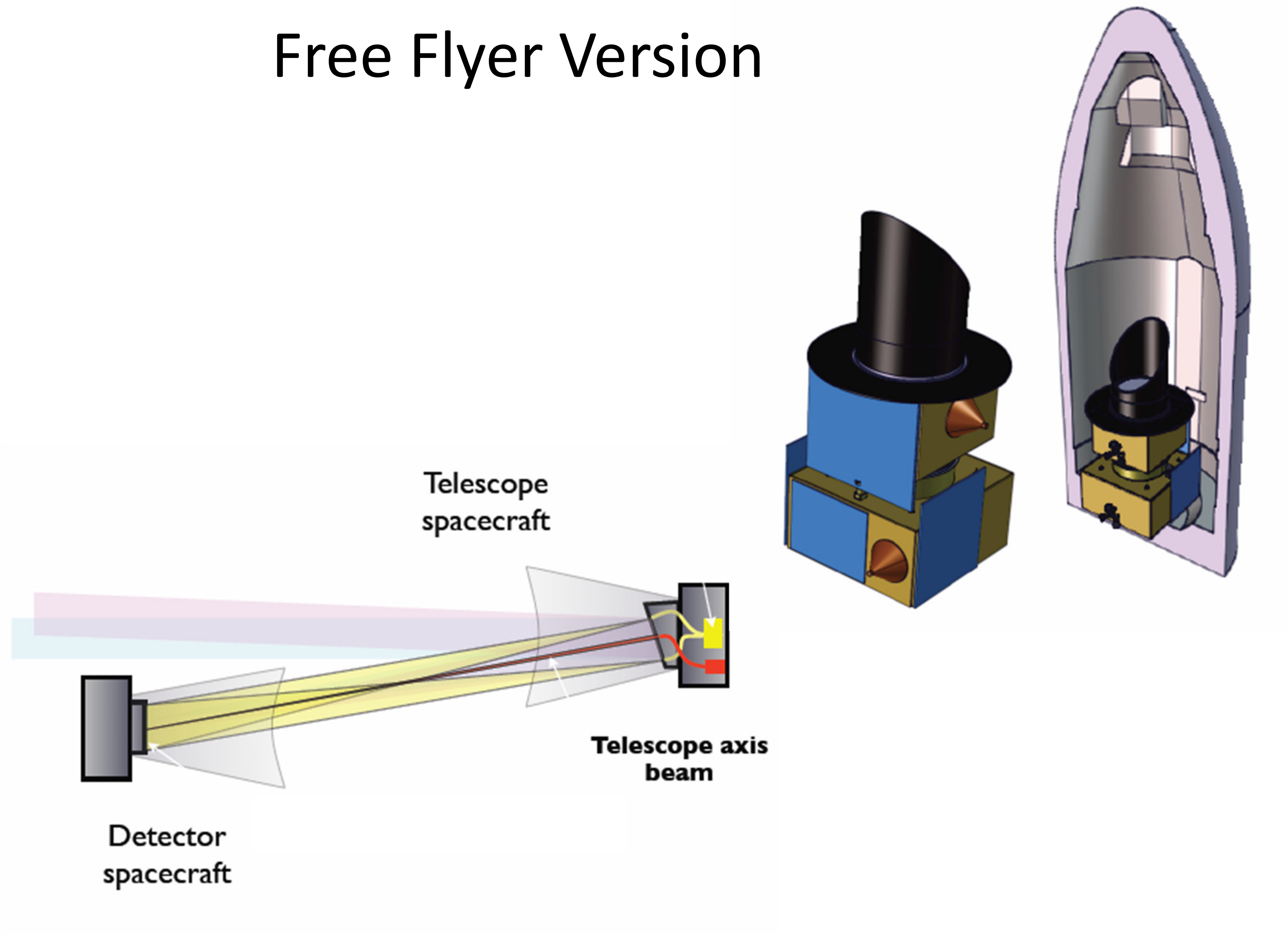
Concept: 1m OAP, 40m focal length, 2 spacecraft fly in formation (L2), or deployed boom (backup)

focal plane of 9 (256*256?) CCDs 8 on X,Y stages. Laser system for focal plane metrology

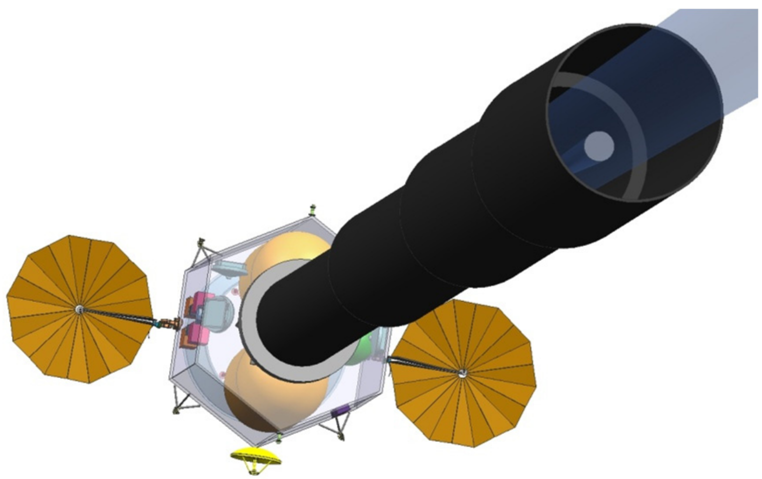
Beamwalk: There's only 1 optic, **no beam walk**
Fibers attached to ULE/Zerodur primary monitors **focal plane geometry**.
Intra-pixel QE/PSF model each pixel modeled with <QE>, and 5 other parameters that specify QE(x,y) within a pixel. **Centroid PSF to 10^{-5} pix**
Photon noise. Brightest 8 stars in a 0.6*0.6 deg box.

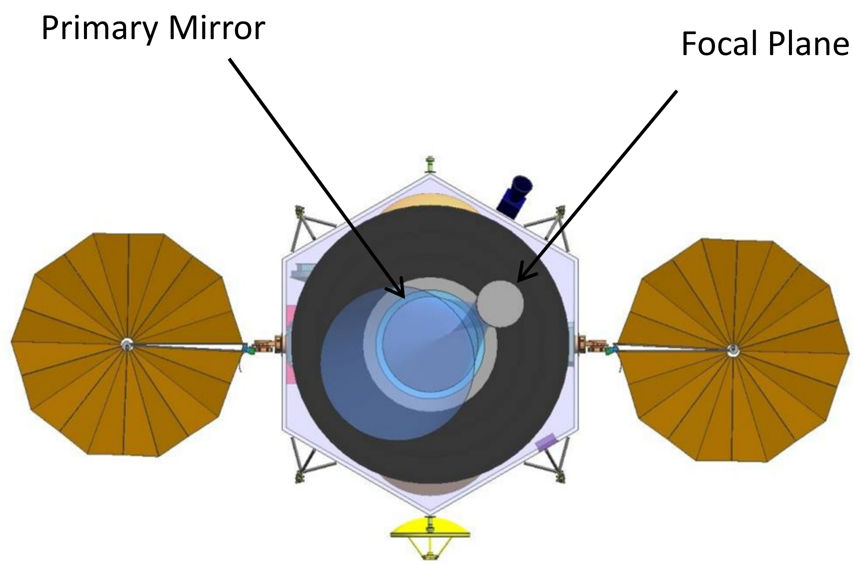
Cost of giga pixel focal plane, replaced by cost of 9 256*256 CCDs and 8 x,y stages

Free Flyer Version



Telescope – Deployed Version

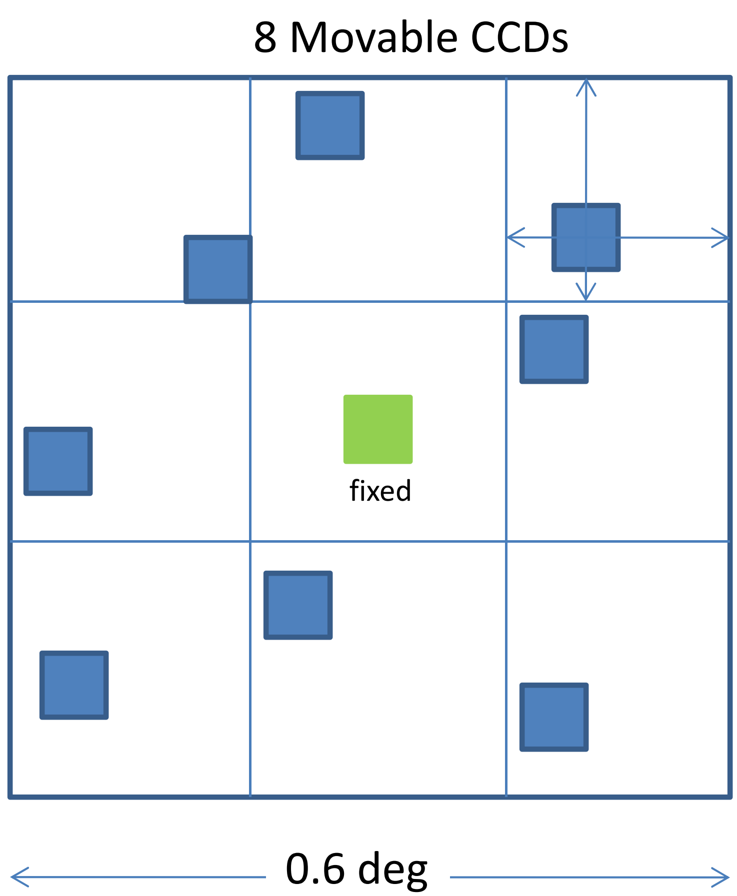




View from Top Looking Down

Fully Deployed Spacecraft

Focal Plane Concept



0.1 uas across 0.6deg is 4×10^{-11}. A **mosiac of CCD's** made of many materials with different CTE, will **not be stable to 4×10^{-11}** for 5 yrs.

even 10^{-5} pix over 4000pix within 1 CCD is 2×10^{-9} difficult

The CCDs for the ref stars move.

Put the star on the same set of pixel(s) at every epoch

Position of CCD monitored by laser metrology across the full FOV

10^{-5} pix over 32*32pix is 3×10^{-7} requires < ~0.1K long term (Si)

We measure the PSF centroid with respect to the laser fringes, using the CCD pixels as an intermediary.

Calibrating CCD Centroiding Errors

- Two classes of errors
  - Pixels move. Measure location of a group of pixels
- PSF centroiding with imperfect pixels
  - QE(x,y,I,j) Intrapixel QE spatial variations for each pixel.
  - Deriving Optical PSF shape
- Simulations of PSF centroiding, assumptions, and how detailed do we have to know the PSF and the QE(x,y) to centroid to ~5e-6 pixels, and how do we make the calibration measurements?
- Initial CCD centroiding results.

Star Centroiding to 10^{-5} pixel

<u>Point Spread Function (PSF) definitions:</u>

- **True PSF**: Image(x,y) at infinite spatial resolution.
- **Model PSF**: Our guess of what the true PSF is.
- **Pixelated PSF**: I(i,j), the integral of Image(x,y)·$QE_{i,j}$(x,y)·dx·dy

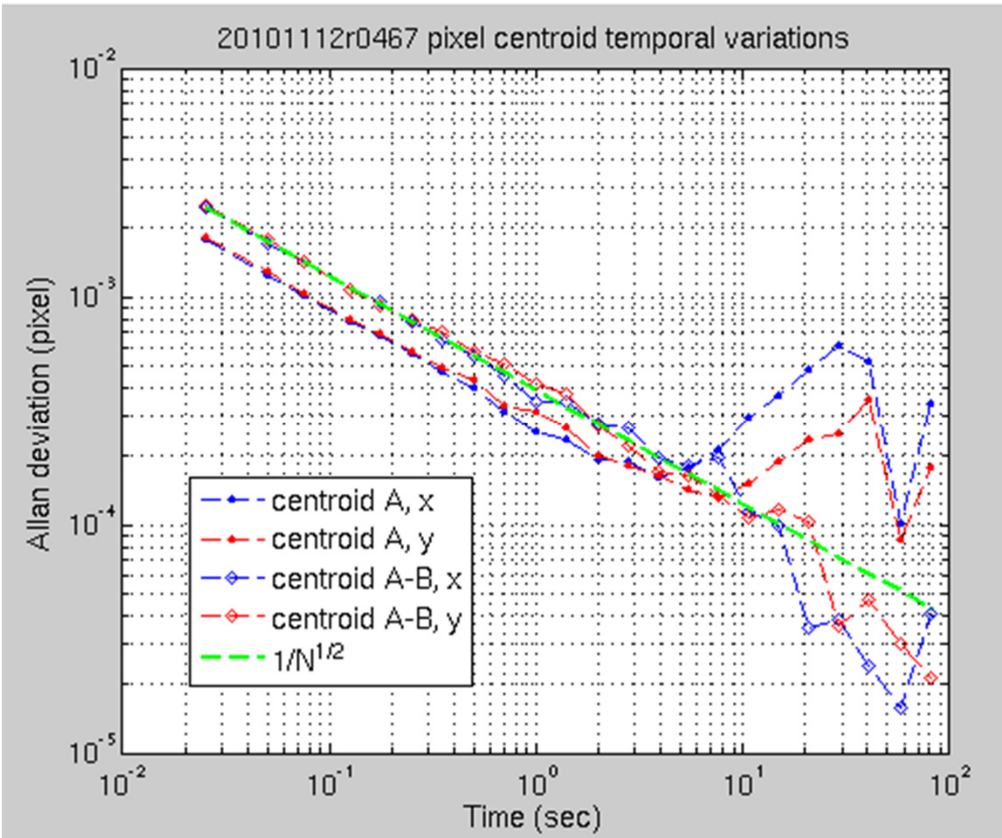
<u>Classical Approach for centroiding</u>:

- Perform Least-Square Fit of CCD data to the pixelated model PSF, fitting for x, y, intensity.
- Known problems:
  - True PSF differs from model PSF, true PSF changes with star color, position in FOV, and as the optics warp. But more important, the model PSF is not the true PSF.
  - Calculating the pixelated PSF from the model PSF requires knowledge of QE(x,y) within every pixel.
  - The canonical approach to measuring QE(x,y) is to scan a spot across each pixel. No done because of practical reasons: can't do all pixels at once, diffraction pattern spills over to next pixel, knowledge of the scanning spot position.

<u>NEAT Approach for centroiding:</u>

- **Nyquist** theorem: Critically sampling a band limited function at greater than 2*bandwidth is sufficient to **<u>perfectly</u>** reproduce that function.
  - We have the knowledge of the **<u>true</u>** PSF in the data, not a **guess** of the true PSF.
- We use laser metrology to measure QE(x,y) for all pixels simultaneously. In fact, we measure the Fourier Transform of QE(x,y), by putting fringes of various spacing and directions across the CCD.
- Numerical simulations show that QE(x,y) calibrated with **6 parameters** per pixel is sufficient for ~2×10^{-6} pixel centroiding for a backside CCD with P-V QE variation <10% across pixel.

Centroid Allan Deviations



Single Fiber centroid reaches noise floor at 3e-4 pixels (drift)
Differential centroid continue to average down to ~4e-5 pixels after 100 sec integration

Details to be published in Proceedings of the Royal Society (British Journal)
Zhai, Chengxing, Shao, M. et. al. Accepted june 2011.

Summary

- NEAT (Nearby Exo-Earths Astrometric Telescope) is a modest sized (1m diameter telescope)
  - Capable of searching ~100 nearby stars down to 1 Mearth planets in the habitable zone, and 200 @ 5 Mearth, 1AU
- The concept addresses the major issues for ultra-precise astrometry
  - Photon noise (~0.5 deg dia field of view)
  - Optical errors (beam walk) with long focal length telescope
  - Focal plane errors , with laser metrology of the focal plane
  - PSF centroiding errors with measurement of the “True” PSF instead of using a “guess” of the true PSF, and correction for intra-pixel QE non-uniformities.
- Technology “close” to complete. Focal plane geometry to 2e-5 pixels and centroiding to ~4e-5 pixels.